Table 5 — Cube shaped formation: UAV initial positions and angles

Initial values	UAV 1	UAV 2	UAV 3	UAV 4	UAV 5	UAV 6	UAV 7	UAV 8
Position	(0, 22, 2)	(−1, 20, 1)	(4, 18, 3)	(3, 20, 3)	(−5, 25, 2)	(4, 26, 1)	(−4,21, 1.5)	(−4, 20, 3)
Angle	(0, 0, 0)	(0, 0, 0.5)	(0, 0, 0.5)	(0, 0, 0.5)	(0, 0, 0.5)	(0, 0,0.5)	(0, 0, 0.5)	(0, 0, 0.5)

Fig. 7 — Cube shaped formation: (a) Entire trajectories, and (b) positions at different time

Fig. 8 — Cube shaped formation: (a) positional errors, and (b) attitude errors

value of the adjacency matrix is depending upon the communication range as well as distance between the i^{th} and the j^{th} UAVs. A comparative result between the constant and the weighted adjacency matrix based directed communication topology is tabulated in Table 6 with respect to the root mean square error (RMSE) for all three situations of every UAV. The combined errors of x, y, and z axes are taken for positional RMSE and ϕ, θ, and ψ angles are taken for attitude RMSE. The results signify that despite of the variation in the communication topology, the proposed formation controller performs satisfactorily.

Comparative Study and Discussion

The comparative analysis is performed with articles [43,18] to demonstrate its effectiveness. In Li *et al.*[43], the multi-UAV system has 4 UAVs (1 leader and 3 followers). To perform the comparative study, the initial conditions and parameter values are kept as same as in Li *et al.*[43] for the follower UAVs. The control inputs are also designed in the paper in line of the dynamic model presented in Li *et al.*[43] The effectiveness of the controllers is compared with respect to the settling time taken by each follower UAVs. The comparative result is tabulated in Table 7. In Li *et al.*[43], the errors along x, y, and z axes settled near $9s$. Whereas, using the proposed formation controller the positional errors settled within $5s$. Along attitude subsystem, the proposed controller performs better than the controller proposed in Li *et al.*[43] In Zhao *et al.*[18], the system consists of 6 followers and 1 leader UAV and communicating

Table 6 — RMSE values for constant and weighted adjacency matrix based directed communication topology

Desired formation	UAVs	Directed topology: Positional error (m)	Directed topology: Attitude error (rad)	Weighted directed topology: Positional error (m)	Weighted directed topology: Attitude error (rad)
Tetrahedron	UAV 1	0.3147	0.0965	0.1955	0.0814
	UAV 2	0.3578	0.0766	0.3247	0.0995
	UAV 3	0.3793	0.0835	0.3083	0.0851
	UAV 4	0.6082	0.0836	0.4798	0.0661
Octahedron	UAV 1	0.5228	0.3404	0.1298	0.0892
	UAV 2	0.6113	0.3576	0.3123	0.0923
	UAV 3	0.3470	0.1918	0.3529	0.1289
	UAV 4	0.3400	0.1482	0.2440	0.1006
	UAV 5	0.4923	0.1827	0.5139	0.1516
	UAV 6	0.3474	0.1560	0.2167	0.0725
Cube	UAV 1	0.1523	0.0798	0.1177	0.0734
	UAV 2	0.2705	0.0890	0.2440	0.0862
	UAV 3	0.3957	0.1231	0.3542	0.1282
	UAV 4	0.2099	0.0947	0.0979	0.0659
	UAV 5	0.5841	0.1620	0.5152	0.1327
	UAV 6	0.5534	0.1393	0.4883	0.0758
	UAV 7	0.7108	0.1231	0.6583	0.1134
	UAV 8	0.6812	0.1317	0.5844	0.1344

Table 7 — Comparative analysis with[43] with respect to settling time

Controller	UAV	x_1	y_1	z_1	ϕ_1	θ_1	ψ_1
Proposed	UAV 1	4.950	1.073	3.255	0	0	0.172
	UAV 2	0.467	0.944	2.175	0	0	0.171
	UAV 3	3.883	0.881	1.478	0	0	0.172
Controller proposed in[43]	UAV 1	8.456	9.005	8.352	0	0	3.981
	UAV 2	8.651	8.902	8.507	0	0	3.474
	UAV 3	8.618	9.013	8.960	4.212	4.395	3.981

Table 8 — Comparison with[18] in terms of Mean error, MSE and MAE of the follower UAVs

Controller	Parameter	Mean	MSE	MAE
Proposed	X	$-2.162 * 10^{-4}$	$3.288 * 10^{-4}$	0.0427
	Y	$4.312 * 10^{-4}$	$3.340 * 10^{-4}$	0.0425
	Z	$1.87 * 10^{-5}$	$2.975 * 10^{-4}$	0.0422
	ϕ	0	0	0
	θ	0	0	0
	ψ	0	0	0
Controller proposed in[18]	X	$7.793 * 10^{-4}$	$2.941 * 10^{-4}$	0.014
	Y	$-1.287 * 10^{-4}$	$5.651 * 10^{-4}$	0.021
	Z	$9.849 * 10^{-4}$	$1.929 * 10^{-5}$	$9.880 * 10^{-4}$
	ϕ	$-6.231 * 10^{-4}$	$3.715 * 10^{-4}$	0.014
	θ	$-1.048 * 10^{-4}$	$5.056 * 10^{-4}$	0.015
	ψ	$-1.464 * 10^{-4}$	$1.330 * 10^{-5}$	$3.100 * 10^{-4}$

through the weighted adjacency based directed network topology. The follower UAVs were moving in a spiral trajectory and making a circular shaped formation. The proposed formation controller is modified according to the dynamic model presented in Zhao *et al.*[18] Similar values are taken for all parameters, initial conditions, and weighted adjacency matrix. In Table 8, the detailed quantitative comparative result in terms of the mean error, the mean square error (MSE), and the mean absolute error

(MAE) of all follower UAVs is presented. As the desired and initial yaw angles are same for all follower UAVs, the formation controller provides 0 mean error, MSE, and MAE along the yaw angle. As the initial ϕ and θ angles are zero, it results to zero desired roll and pitch angle. So, the mean error, MSE, and MAE along the roll and the pitch angles are observed to be 0 throughout the time for all follower UAVs. The mean error, MSE and MAE along x, y, and z axes are also satisfactory with respect to the controller developed by Zhao *et al.*[18] So, it is to be mentioned that the proposed distributed formation controller provides efficient results and works satisfactorily on different dynamical models too.

Conclusions

A control paradigm of a multi-UAV system is discussed in this paper for formation control. The proposed controller is asymptotically stable and the proof is provided through satisfying conditions of Lyapunov criteria. The communication network among UAVs is represented through the constant and the weighted adjacency matrices based directed graph topologies. In weighted adjacency matrix, the distance between the UAVs also influences the adjacency matrix calculation and in control input design. The proposed distributed formation controller is validated through varying numbers of the UAVs to achieve and maintain different desired shape of formations. Simulation results illustrate that the proposed formation controller works satisfactorily. The comparative study is also presented for both the directed and the weighted directed communication topologies and it is observed that it performs satisfactorily over other controllers for the same initial conditions. The potential scope of improvement is to develop a robust formation controller while the effect of disturbance is unknown on the system's dynamical model. The efficiency of the proposed formation controller can be tested through switching network topology-based connection where the type of the topology among the UAVs changes from undirected to directed and vice-versa as per the application. The proposed controller is asymptotically stable. The further scope of extension is to propose a finite-time formation controller. Finally, this work can be extended to implement on the hardware system.

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